Passivation, Transition Width, and Noise for YBCO Bolometers on Silicon

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***Abstract*—We are developing $YBa_2Cu_3O_{7-x}$ (YBCO) thermometers for large area bolometers that include a heater for calibration by the electrical substitution of power. Because YBCO on buffered Si is under mechanical stress and must be very thin to avoid cracking, we find it is electrically sensitive to its passivation layer. For example, passivation by $SrTiO_3$ raised the noise in our films by about a factor of 100. An alternative is to first cap the YBCO with Au for passivation, and then add an insulator for electrical isolation. Such devices have a narrower transition width, by a factor of 3.9. A model with a shunt resistor across the superconductor predicts a narrowing of the transition, but by less than the observed amount. The noise equivalent temperatures of our thermometers, about 4 nK $Hz^{-1/2}$, are not degraded by the normal metal shunt, although the resistance is decreased. The resistance can be raised using AgAu alloy in place of Au, with equivalent noise performance.**

INTRODUCTION

We are extending development of high-T_C bolometers by making a large area device, 4 mm square, with good responsivity at a chopper frequency of 10 Hz, and the added feature of a thin film heater for calibration by the electrical substitution of power. Electrical calibration has been used in a high-T_C radiometer based on a Cu cavity absorber [1], which gives a much slower response, a time constant of 75 s instead of the milliseconds of our thin film devices.

PASSIVATION

Here we focus primarily on the problem of passivating the superconductor YBCO so that a heater can be fabricated on it without unduly degrading its noise equivalent power (NEP). YBCO is sensitive to water and atmospheric water vapor [2-4]. For example, a bulk sample exposed to 85% relative humidity at the modest temperature of 85 ˚C for 90 min is damaged to a depth of 320 µm, as observed in its x-ray diffraction intensity. Fortunately, epitaxial YBCO, like we use, is less sensitive to water but we must nevertheless be concerned because our YBCO films are less than 0.1 µm in thickness. Ordinary lithographic processing may damage them.

Interesting x-ray analyses have been done on the surface reactions of YBCO thin films in the atmosphere [5] but the more pertinent research for us is a comparative study of aging of YBCO films on different substrates [6]. In that comparison the YBCO film thicknesses on all substrates were much the same as we use, 50 nm, because of the limited film thickness allowed on Si substrates to avoid film cracking from differential thermal expansion. That study evaluated the quality of the YBCO films by their lattice perfection, normal state resistivity, critical current density, and long term stability. YBCO on $SrTiO_3$ (STO) was the best in all categories and YBCO on Si was the poorest. In the latter case a thin buffer layer of yttria stabilized zirconia (YSZ is ZrO_2 with 10% Y_2O_3) was used to avoid chemical reactions between the YBCO and Si. But this YBCO deteriorates rapidly when it is in contact with photoresist for patterning and during etching. Thus, passivation is essential to avoid deterioration of YBCO films from processing and aging. Measurements of the stability of YBCO films on other substrates do not apply to films on Si. To keep a practical perspective on passivation, however, note that we have already demonstrated that thermometers on Si give excellent noise performance over the short term if there is no further processing [7].

For the larger problem of fabricating an electrical substitution heater on a YBCO thermometer, we are developing a two-step process, first passivation and then insulation. However, our first attempt at passivation was to deposit polycrystalline YSZ on YBCO at room temperature. Subsequent processing included KOH etching of the back side (opposite the YBCO) of the Si chip using an O-ring seal to confine the etchant to that surface. Etching at a temperature of 80 ˚C for 2 h 15 min reduced the supporting Si to a thickness of 2.8 µm, the depth of the B doping. After this processing the YBCO was no longer superconducting at 76 K. Thus poly-YSZ does not adequately passivate our YBCO, but it was not determined what produced the damage. The likely candidates are the processes of masking the chip with photoresist, with a bake at 110 ˚C for 10 min, or the longer heating for KOH etching.

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The most common passivation used with YBCO in our laboratory is epitaxial STO on YBCO on $LaAl_2O_3$ substrates. We developed a fabrication method for STO passivation that was compatible with our desire for *in situ* deposited Au contacts at the periphery of the device. The STO deposition employed a "hot" mask, a moveable shadow mask that was in thermal contact with the 850 ˚C substrate. However, the YBCO thermometers that we fabricated with this mask had high noise, about a factor of 100 higher than unpassivated devices. This result is consistent with the finding, mentioned above, that YBCO on Si is less stable and chemically more reactive than on more favorable substrates. The apparent reaction in this case is with the deposited STO.

An alternative explanation is that the hot mask caused the extra noise by contaminating the films. That seems unlikely because the mask was made of the same high-temperature alloy as the heater block on which the substrate is bonded, so this material has always been nearby during depositions. Also, the mask is not as hot as the heater block, it does not have the red glow of that block.

Chang, et al. [8-10] have shown that YBCO thin films, with MgO and YSZ substrates, can be passivated against water by coating with a normal metal, 100 nm of Ag. We decided to test passivation of YBCO on Si (with the usual CeO_2 and YSZ buffer layers) using a very thin layer of Au on top. This had a beneficial effect in spite of the fact that the normal metal shunts the YBCO.

EXPERIMENTAL RESULTS

Figure 1 shows the derivative of the YBCO resistance with respect to temperature, versus temperature, for several devices. Data from both unpassivated and passivated YBCO are shown. Summary data for these thermometers are given in Table I, where it is seen that they have very low noise. The narrower transition of the passivated device, with a full width at half maximum of 0.38 K versus 1.66 K for the unpassivated device, can be explained in part by the effect of a shunt resistor mimicing the Au shunt. In the inset of the figure we repeat the data of (a) and also show, as the smaller peak, the effect of hypothetically shunting that device with a resistance that gives the same asymptotic resistance as the passivated device (b). The effect of the shunt is to electrically short the high resistance (high temperature) part of the transition, which narrows its width. However, both the narrowing and the peak value of dR/dT are less, by a factor of 2, than the corresponding values for the passivated device. Some variation of transition width is expected from one device to the next, but such variations are the order of 30%, not a factor of 2. Consequently, our data imply another effect: superconducting film quality is enhanced by *in situ* passivation. Chang has suggested that the normal metal migrates to the grain boundaries of the superconducting film [8-10], but that remains to be proven.

In Table I we list the properties of four devices we have tested using measurement apparatus described previously [7]. The main figure-of-merit we prefer is the noise equivalent temperature for the thermometer,

$$NET = V_n \Big/ I \frac{dR}{dT}, \tag{1}$$

where V_n is the voltage noise per root hertz (at 10 Hz) of the device with current bias I, and dR/dT is the temperature derivative of the device resistance R. A related figure-of-merit is (1/R)dR/dT, which is of interest partly because it is a property of the superconductor that is depends only on sheet resistance and not the detailed geometry. A deeper reason is that V_n has several parts: amplifier noise, Johnson noise, and excess noise. Excess noise is proportional to the bias current [11], which implies that it is proportional to R. For that reason (1/R)dR/dT contains the dependence of NET on R if the excess noise dominates. Maximizing (1/R)dR/dT minimizes NET in that case.

To establish that our Au layer passivated the film against further processing, we patterned photoresist on the device and deposited MgO insulator and a PdAu heater, both at room temperature. We measured the device properties before and after the final two depositions, with nominally the same bias current. These results are listed in Table I for the 4.0 × 7.6 mm device. The transition width and the peak dR/dT were slightly increased by the processing, but the NET remained essentially unchanged. With increased bias current the NET decreases to 6.1 nK $Hz^{-1/2}$, a value within 25% of the best unpassivated thermometer, which is the 5.0 × 7.5 mm device. Unfortunately, we found that the heater was not electrically isolated from the thermometer, probably because of pinholes in the insulation.

Using another passivated device, we measured the NET before and after etching of the Si beneath the detector, for thermal isolation. With a bias current of approximately 5 mA, to avoid self heating after thermal isolation, the NET was nearly the same after etching of the Si, having increased by no more than 10%. (Note that all other measurements reported here are for thermometers on thick Si, not Si membranes.)

Comparing the 5.0 × 7.5 mm unpassivated thermometer with the 4.0 × 7.6 mm passivated thermometer with

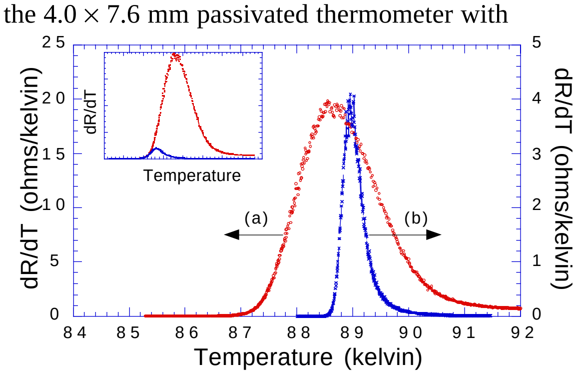

Fig. 1. Temperature derivatives of YBCO resistance vs. temperature. (a) Data for unpassivated YBCO 5 mm wide by 7.5 mm long with 20.3 mA bias. (b) Data for YBCO passivated with 20 nm of Au deposited *in situ*. Sample is 4 mm wide by 7.6 mm long with 9.77 mA bias. The large peak in the inset figure is a repeat of the data from the unpassivated device, (a). The smaller peak is data for a hypothetical device computed by effectively shunting the YBCO with 1.8 Ω.

TABLE I
PROPERTIES OF YBCO THERMOMETERS FABRICATED ON SILICON SUBSTRATES

Sample Width × Length (mm)	Bias Current (mA)	Transition Width (K)	T(K) for Peak dR/dT	Peak dR/dT (Ω/K)	R (Ω)	(1/R)× dR/dT (K^{-1})	V_n (nV/√Hz)	System NET (nK/√Hz)
Unpassivated Thermometer								
5.0×7.5	10.1	1.55	88.70	22.0	13.85	1.6	1.297	5.97
	20.3	1.66	88.60	19.4	13.64	1.4	1.835	4.66
Au Passivated Thermometers								
4.0×7.6	9.77	0.38	88.95	3.90	0.634	6.2	0.527	13.9
(with MgO	9.70	0.46	88.62	5.00	1.04	4.8	0.590	12.1
insulator)	20.9	0.57	88.47	4.30	0.964	4.5	0.550	6.1
4.0×4.0	9.92	0.37	88.33	2.25	0.395	5.7	0.470	21.0
	20.8	0.47	88.32	1.90	0.391	4.9	0.460	11.6
	50.3	0.51	88.10	1.70	0.403	4.2	0.390	4.60
	50.2	0.51	88.10	1.70	0.403	4.2	0.372 ±.040	4.36 ±.47
AgAu Passivated Thermometer								
4.0×4.0	9.71	0.74	88.90	4.15	1.33	3.1	0.702	17.4
	20.9	0.75	88.77	4.30	1.33	3.2	0.403	4.48
	20.9	0.75	88.77	4.30	1.33	3.2	0.404 ±.030	4.49 ±.33

nominally the same current of 10 mA, we see that the passivated device has a factor of 3.9 improvement in (1/R)dR/dT, but the NET is not improved, contrary to the argument given above. This suggests that excess noise is not dominant in the latter device. That is confirmed by increasing the bias current by a factor of 2 (in the device with the MgO insulator) and finding that the noise voltage does not increase. The largest contributor to the noise is the preamplifier [7], with a voltage noise of 0.35 ± 0.02 nV $Hz^{-1/2}$ and a current noise of 31 ± 4 pA $Hz^{-1/2}$, at 10 Hz.

The next point of interest in Table I is a comparison of two 4 × 4 mm samples, one passivated with 20 nm of Au and the other with 20 nm of AgAu alloy (50-50 atomic percent), which has higher resistivity. As the bias current is increased in the Au passivated thermometer, the transition broadens and the peak value of dR/dT decreases somewhat, but the NET steadily improves (decreases), approximately inversely in proportion to the bias current. With 50.2 mA bias we did an extended data run at fixed temperature to accumulate statistics on the noise at 10 Hz, with the resulting uncertainties given in the noise voltage and System NET columns.

The AgAu-passivated thermometer has 3.3 times the resistance of the Au-passivated device but about the same preamplifier limited NET. In the passivated devices the bias current was limited to avoid self heating, but we achieved amplifier-limited NET's in both cases.

CONCLUSIONS

A very thin layer of Au is sufficient to passivate YBCO on Si. The lowest NET's obtained, 4.36 ± 0.47 and 4.49 ± 0.33 nK $Hz^{-1/2}$, are remarkable because they are as low as any numbers previously reported for NET, and also because the contributions from the thermometers are a small part of the NET's; the noise is dominated by the preamplifier. Thus, passivation with normal metals does not degrade the performance of thermometers, it improves them.

For thermally isolated thermometers, as in bolometers, the bias current will be limited by self heating, depending on the thermal conductance that is used. This limitation on current can be eliminated by using voltage bias [12,13], which requires higher impedance thermometers if a transistor preamp is to be used. The advantage of alloy passivation is its higher resistance, which when patterned to a meander line, facilitates noise-impedance matching for the measurement of device current. Our results are competitive with those obtained with smaller thermometers using the inhibit fabrication process [14] and passivation by PtO_X [15-17].

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